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To cite this version:
R. Moreau. THE IMPACT OF VERY STABLE OSCILLATORS ON NAVIGATION SYSTEMS. Journal de Physique Colloques, 1981, 42 (C8), pp.C8-415-C8-426. <10.1051/jphyscol:1981847>. <jpa-00221743>

HAL Id: jpa-00221743
https://hal.archives-ouvertes.fr/jpa-00221743
Submitted on 1 Jan 1981

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THE IMPACT OF VERY STABLE OSCILLATORS ON NAVIGATION SYSTEMS

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Abstract.- The high stability achieved by oscillators driven by quartz or by
atomic transitions is such that their time scales, when used in navigation
systems, remain coherent at all locations. For that reason, it is no longer
necessary to provide either for transfer of the time parameter by radio waves
from station to station and from station to vehicle, or for its treatment as
an additional unknown in the equations. This situation makes it possible to
constitute time frequency navigation systems with many advantages, namely
direct access to circular or spheric modes, this possibility giving higher
accuracy and reduced sensitivity to geometric parameters.

Introduction.- Navigation systems aim at making it possible for a mobile to determine
its position relative to landmarks related to a reference frame (terrestrial, solar,
absolute). These landmarks may have been especially established to this end ; it is
the case in particular in the OMEGA, LORAN C or NAVSTAR systems ; they may also be
natural, but identifiable through appropriate techniques.

Two groups of systems may be distinguished :

a) active systems, with on-board transmitter : beacons, radar transponders,
b) passive systems, without transmitter, but only receiver on-board.

The second group of devices is discreet, i.e. it does not risk to entail spotting of the vehicle by detection of its RF emission.

Positioning devices are the reciprocal of navigation devices ; their function
is to allow an Earth-bound or space station with proper reference to determine the
position of a mobile (navigation in channels), and possibly to send back its position
to the mobile.

Although the ranges, positions and various other characteristics are often
quite different for positioning and navigation systems, their functional structures
are very similar and the geometrical and physical principles involved are the same,
so that we shall not separate them here and this paper, which aims at bringing to
light the influence of oscillator stability on their performance, will make no differ-
ence between them.
General principles used.- A point in space is defined by the intersection of \( n \) surfaces, with \( n > 3 \). These surfaces are either hyperbolae, or ellipses, or spheres. Most often, in the present state of affairs, they are hyperbolae; it is the case in particular for the LORAN C and OMEGA systems.

The surfaces are concretized by equalities of phase when the systems operate in CW (Continuous Wave), or of propagation time when they operate with pulses of RF signals. It often happens that a given system uses quasi simultaneously both modes.

The systems differ by the type of surface generated and the means implemented for measuring either phases or propagation times for spherical systems, or differences or sums of phases or propagation times for hyperbolic or elliptic systems.

Survey of the role of oscillators in navigation systems and their derivatives.- Oscillators are devices whose successive and periodical changes of state serve as a basis to two broad classes of applications [1].

In the first class, the rhythms they generate are used for triggering sequences of operations; it is for instance the case of clocks controlling the distribution of time intervals during multiplexing operations.

In the second class, the characteristics of the signals generated (phases, frequency, amplitude) carry the information it is intended to acquire or transmit.

The RF waves which concretize the surfaces whose intersections define the vehicle position are generated by oscillators, so that their characteristics happen to be transferred to those of the RF waves; in particular the stability of the emitted wavelengths -hence of the network of RF reference points exploited by the navigation systems- is obviously related in a direct manner to the frequency and phase stability of the pilot used.

Phase or time are linked to the frequency stability of oscillators by the relationship:

\[
\Delta t \text{ or } \Delta \varphi = \int_0^t \frac{\Delta f(t)}{f(t)} \, dt \implies \Delta t(t) = \Delta t_0 + \left( f_0 - f_r \right) t + \frac{a t^2}{2} + \sum(t)
\]

with:
- \( \Delta t \) = time error at time \( t \),
- \( \Delta t_0 \) = initial time error,
- \( f_0 \) = initial frequency at time \( t = 0 \),
- \( f_r \) = reference frequency (desired),
- \( a \) = aging, or drift rate,
- \( \sum(t) \) = variance of time fluctuations, due to various kinds of noise (white, flicker, random walk);

in particular, a linear frequency drift creates a quadratic time drift [8].
Moreover, there exist stability thresholds authorizing structures more advantageous than others. It is in particular the case of devices where the position of the mobile is defined by the intersection of three spheres.

In fact, the consequences of the performance of the oscillators used in navigation systems are multiple and complex, and we shall emphasize them briefly, starting by a listing of the main characteristics of radiolocation systems.

We may divide the characteristics into two groups:

1 - functional characteristics, comprising:
   . range,
   . precision \{ absolute,
     \{ relative,
   . spatial homogeneity (dilution),
   . reliability;

2 - logistic characteristics:
   . availability,
   . exploitation constraints,
   . existence of downgraded modes,
   . discretion (one way),
   . vulnerability (codes, stability, etc.).

Impact of oscillator performance on navigation system characteristics. - We shall briefly analyze the impact of the performance of very stable oscillators on each of these characteristics.

\textbf{Range, precision, dilution, reliability}

\textbf{Range, precision and dilution} (or spatial inhomogeneity of error) are hardly dissociable parameters which are simultaneously affected by oscillator stability, as will be shown by the following comments.

The principal parameters which govern these factors are:

- transmitter power,
- wavelength retained,
- receiver detectivity,
- system structure,
- station location,
- oscillator stability.

The first three points will not be discussed and will be assumed once and for all, and we shall analyze briefly the influence and imbrication of the other three on the performance of a navigation or positioning system.

If we consider a trajectography system of hyperbolic type and if, for simplification, we examine the problem in a plane (fig. 1), we can see that the precision with which the position of a mobile is determined - if we neglect for the moment the other causes of error, in particular those due to propagation, to relativity and to the signal/noise ratio - is related to the angle between hyperbolae at their intersection: it rapidly gets downgraded whenever the mobile is further from the polygon made by the three stations A, B, C. This fact is particularly clear for points located in the hatched zone.
In a more precise way, calculations performed in the case of a three-dimensional structure [2] such as that represented on figure 2 enable one to define error coefficients, figures by which should be multiplied the wavelength used in order to obtain the error, in metres, for a given precision of phase or propagation time measurement.
Figure 3 is graduated in reduced space scale (the measuring unit being the distance between stations). The dotted curves correspond to the hyperbolic structure, and show how fast the positioning is downgraded when the mobile gets further from the stations. The solid line curves correspond to a structure exploiting a transponder on the mobile, which leads to defining its position by the intersection of three spheres.

The comparison of the coefficients of the two networks shows the enormous advantage of spherical (or circular) structures over hyperbolic structures, and justifies the present general trend towards creating circular or spherical navigation systems.

It is easy to show that these structures are all the easier to implement as the oscillators generating the RF waves are more stable. The simplest spherical device may indeed be made of three stations equipped with very stable, mutually synchronized oscillators, the mobile carrying itself a fourth oscillator, also synchronized with those of the stations; in these conditions, the operation of the system is illustrated by the diagram of figure 4.
Because of the supposedly perfect stability of the oscillators, the time is the same on each station and on the mobile; thus, at a time $t_0$ known on the mobile, three RF pulses $a, b, c$ are transmitted by the stations $A, B, C$; these are received on the mobile after delays $\tau_A, \tau_B, \tau_C$ depending on the relative positions of the mobile and stations.

It is obvious that the mobile position looked for is at the intersection of three spheres of respective radii $C\tau_A, C\tau_B, C\tau_C$ ($C$ being the speed of light).

We thus have the simplest spherical system, but this depends entirely on the relative stability of the oscillators constituting them.

All present-day systems are based on a compromise between oscillator stability and the synchronization frequency required for obtaining the desired precision: the better is the stability, the less frequent may be the synchronizations.

The necessity of synchronizations is anyway very penalizing as it considerably complicates the systems, and may even sometimes be incompatible with logistic requirements.

To illustrate this we may say that the typical value of precision gain to be expected by passing from a hyperbolic to a spherical structure for distances of 3 to 4 intervals between stations is of the order of 10.

If the structure is elementary, such as that described above, the relationship between oscillator stability and positioning precision is immediate; it is illustrated for a particular case on figure 5. In this diagram the figures marked on the curves are metres per nanosecond of error, whether this error is due to measurement uncertainty on propagation time or a synchronization defect due to a relative instability of the oscillators. It can be seen that, for distances of 3 to 4 intervals between stations, the error is of the order of 2 metre per nanosecond.

![Diagram](image-url)
To have an idea of the required stabilities we must define the mission duration: for aeronautical missions, it is counted in hours, but for maritime or space missions, in months or years. It is easy to calculate that for such an elementary system the required long-term stabilities may reach one microsecond per year in the operating conditions created by the environment: such a value, to my knowledge, is not easy to obtain with the present technology.

The main navigation systems operating now or in the near future are:

- DECCA, very much used by fishermen, has a medium precision and will not be commented here.

- LORAN C (Long Range Aid to Navigation): the ground stations are mostly equipped with cesium clocks synchronized by groups of 3 or 4 by clock transport several times a year. Synchronization is maintained to within about 1 microsecond. It is a hyperbolic system which, in some particular cases, may be rendered circular (fig. 6).

- OMEGA is a very long range navigation system, hyperbolic in principle, (fig. 7). The transmitting stations comprise four cesium jet oscillators, and the combined output of these four standards forms a signal whose relative drift is of the order of $10^{-12}$. But this system can also be used in circular mode. Two techniques can be used: [4]: direct phase measurement of the signals from each station used (which requires a very stable clock synchronized to the A transmissions), or phase measurements of the signals from station pairs. The result of the first method is a family of circular lines of position (LOP's) centered about the station and spaced one wavelength apart. The second technique yields a family of hyperbolic lines of position spaced one half wavelength apart.

- TRANSIT is a navigation system by quasi polar satellites: there are 5 satellites in orbit and the user, to get a fix, must remain in contact with the satellite over an arc of orbit of several minutes of time. The satellite is equipped with a quartz oscillator of good quality ($10^{-11}$). This system is deemed insufficient and is to be replaced by NAVSTAR (NAVigation Satellite Time And Ranging system) or GPS (Global Positioning System). This system involves 18 satellites so that several of them can be heard simultaneously by the users. Each of the four satellites launched contains three rubidium atomic clocks [3]; the fourth satellite also has an experimental cesium atomic clock. The correction can only be made when the satellite is in view of the control center about every 12 hours.
The system is such that many modes of utilization, including spherical modes, are possible, according to the user's equipment.

The stability required for the spaceborne oscillators is defined by the necessity of limiting the updating frequency and of allowing an autonomous operation, without control from the ground, for at least two weeks.

The contribution of the spaceborne clock stability to positioning precision in the case of type P (Precision) signals is still under study. It is estimated at 5 metres with a 68% probability two hours after update, and 12 metres twenty-four hours after.

As for the ground (user) clock, the required quality obviously depends on the utilization mode, but the most interesting characteristic is in this case the medium-term (30 seconds to 10 minutes) stability: this should be of the order of $20 \times 10^{-9}/600 \approx 3.10^{-11}$ to be coherent with the space segment; this means that a good quality quartz may be suitable.

Reliability. Thus, the oscillators used in this system have a stability just sufficient for the expected objectives; on the other hand, the present-day reliability is not yet satisfactory.

It is indeed a major problem in navigation systems to be able to guarantee the pilot stability in the environmental conditions imposed by the system, and their proper operation during the whole duration of the planned missions, with a sufficient probability. In the case of GPS, the planned lifetime is six years, and this value seems to be able to be reached only through redundancy (3 or 4 clocks per satellite). Moreover, their behaviour should be modelled so as to account for the drifts in the navigation message.

Thus it is clear that at the present time the critical path as regards reliability passes through the oscillators, the reliability of the navigation system being finally that of the clock. It would be useful to investigate, but this is outside the scope of this paper, whether the clock stability is conditioned by the resonators, quartz or atomic cell, or by ancillary equipment, such as electric supply.
There is no question to review here all the navigation systems, which are very many (several tens), which anyway means that there is no universal one and that the field of application of each is often limited (such as TORAN for oil exploration).

**Logistic characteristics**

The availability of a navigation system can be numerized by the time percentage during which an user located anywhere on Earth is able to compute his position.

It thus exists a space availability and a time availability; the former is defined once and for all, and thus accepted once the reference segment is set in place: ground segment for OMEGA [4], space segment for GPS [5]; only GPS, when fully operational, will offer a worldwide covering, hence a 100% space availability. Its time availability is also expected to be 100%, but it is directly related to the reliability of the space segment hence, as already mentioned, to oscillator reliability.

For comparison, the time availability of the TRANSIT system is at best 10% (10 minutes every 2 hours), and the space availability (covering) of the order of 30% (?).

Unserviceability of one satellite, for instance through clock breakdown, is expressed in GPS by a loss of precision, due to the existence of downgraded operation modes, while in the TRANSIT system there would be a concomittant reduction of availability.

One of the main operational constraints of the above navigation systems is the necessity to perform periodically either clock synchronization -case of LORAN C or OMEGA- or monitoring and modelling of their drift- case of GPS- by means of a sophisticated and costly control segment. It is obvious that this constraint is reduced when the long-term oscillator stability is increased.

For the users, the operational constraint which seems most directly related to the stability of the vehicle borne clocks is the computing capacity necessary for obtaining a given precision. Indeed if we may consider the time and frequency generated by the vehicle borne oscillator as exactly known, approximately known or totally unknown, the required computing capacity increases considerably, and one passes from the microcomputer to the heavy minicomputer. Whereas this is of little importance for a submarine or an airliner, it is not so for a trawler or fourth-level aircraft.

**Discretion**, i.e. the faculty of a mobile to get a fix without emitting any RF signal, is a quality much appreciated by the military. It is the case of the astronomical fix, and also of passive systems where the user is only equipped with a receiver. This constraint imposes to the discreet navigation system to be hyperbolic if it is equipped with only medium stability oscillators, or possibly spherical if it carries high stability ones.

Consequently, discreet and precise systems must be equipped with very stable oscillators.

Thus, the discretion concept implicitly assumes that the RF information travels from stations to vehicle in one sense only (there is no transponder): discreet systems are "one way" systems, with all the advantages this implies [1], but it should not be forgotten that, at the present time, the most precise systems make use of the "two way mode" technique as soon as the mission duration exceeds a few days.

**Vulnerability** is a concept corresponding to the sensitivity of the system, or its components, to external agents, whether these are natural - and in this case this concept is none other than the reaction to influence parameters (temperature, vacuum, radiations, magnetic field, etc.) - we shall not emphasize this aspect- or they are artificial, i.e. purposely created with a view to render the navigation system inoperative: this is in particular the case of RF jamming. Very stable oscillators
are more jam-proof, as their stability makes it possible to generate codes optimized 
for this objective without fearing that the residual instability of the pilots 
jeopardize their efficiency, particularly by creating secondary rebounds in the 
ambiguity functions [9], which is expressed by a loss of precision due to a deterio-
ration of the signal/noise ratio.

**Downgraded modes.** It should also be emphasized that the use of very stable 
oscillators in navigation systems makes easier the constitution of redundant devices: 
indeed if the oscillator stability is sufficient for the source frequencies (and 
phases) to be considered as known, it is no more necessary to transmit them, so that 
the systems comprise less functional components and hence are easier to be made reliable by multiplication of modules.

Moreover, the structure of the system may itself be simpler— one way system—
so that it is possible to consider downgraded operation modes without excessive 
complication; the downgraded mode of a spherical system, for instance, may be the 
hyperbolic system to which we would have to resort if, for any reason, the stability 
of the source became insufficient: there would result a loss of precision, but not 
a total loss of information.

This brief analysis clearly shows that the performance of navigation systems 
is largely dependent on the characteristics of the oscillators that govern them, but 
these do not possess yet all the desirable qualities.

**Prospective.** In the very near future most navigation systems will be of the "time-
frequency" type; this means that they will be able to exploit simultaneously or suc-
cessively the information carried by the phase of an RF signal (time) and that carried 
by the time derivative of the phase (frequency) of this same signal.

The denomination "time-frequency" is also often used for some synthetic systems 
including, on-board an aircraft, a spacecraft or a ship, many functions such as 
telecommunications, navigation, identification, anticollision, etc. These are, in 
fact, multifunction systems using "time-frequency" techniques. They are organized 
around three main modules:

- a very stable oscillator,
- a minicomputer,
- a transmitter-receiver module.

The generalized use of these concepts supposes that present-day components, 
particularly oscillators, progress rapidly.

**Near future**

It is desirable that, in the near future, very stable oscillators be more comp-
act, but above all more reliable and easier to model; this means that their behaviour 
should be studied in various environmental conditions (accelerations, vibrations, magnetic fields, temperatures, etc.), and that the laws of their evolution in time 
be established with a view to be able to input into the memories of their associated 
computers the necessary correction factors. It should be remarked that it is anyway 
indispensable to take into account some corrections, in particular relativistic 
corrections which are far from negligible: they can reach on Earth several hundreds 
of nanoseconds; by way of indication, the formula providing the calculation of the 
relativistic drifts \( \delta \) occurring between a fixed clock and a mobile clock travelling 
around the Earth at a latitude \( \lambda \) and an altitude \( h \) may be expressed in the following 
way [10, 11]:

\[
\delta = \left( \frac{9h}{c^2} \right) - \left( \frac{(2R \Omega \cos \lambda + \nu)}{v} \right) \frac{v}{2c^2}
\]

Furthermore, a particular effort should be made to improve the long-term stabil-
ity just sufficient for applications to navigation; an overall value of \( 10^{-13} \) 
for \( \Delta f/f \) should be ensured over a year in "aviation" type environmental conditions.
Figure 8 shows the predictable medium term evolution of the most common oscillators.

At longer term

It seems to me desirable that time distribution be organized at a worldwide basis at the level of one (maybe ten) nanosecond, so that the many applications of very stable oscillators, particularly those related to navigation, might develop appropriately. If such a network existed -GPS is likely to provide this precision... but GPS is considered as vulnerable-, and provided that the long-term stability of very stable oscillators had been improved to close to $10^{-14}$, nothing would hinder anymore the full exploitation of the "time-frequency" principles; the problem of synchronization updating would be suppressed, and navigation devices would be extremely simple and economical; under the effect of increasing number of users, very stable oscillators (not necessarily atomic) might become inexpensive and applications in the general public could be considered: general aviation, trawlers, pleasure boats, etc., with a direct impact on the traffic safety.

On the scientific viewpoint the increase of the short-and long-term stability of very stable oscillators conditions in a large measure the progress in the knowledge of cosmic laws and the possibility of carrying out the necessary experiments by controlling with a presently inaccessible accuracy the trajectory of space probes: let us mention as an example that a "one way" navigation device for a Mars probe aiming at a precision of a few meters requires a long-term stability of $10^{-15}$.

On the military viewpoint, apart from the "conventional navigation" motivation which requires oscillators with an excellent long-term stability, requirements appear on short-term stability for navigation systems using pattern recognition techniques, such as systems derived from "Side Looking Radars".
Conclusion.- The brief study which has been presented leads to two remarks, which will serve as conclusion:

1 - Navigation system progress as regards precision, simplicity, reliability and universality is conditioned by progress on very stable oscillators.

2 - The performance attained at present by atomic or quartz very stable oscillators are not only not superabundant, as sometimes believed, but still insufficient for their utilization in navigation systems to be fully generalized.

References.-


